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AN EXPERIMENTAL INVESTIGATION OF
THE SENSITIZATION OF ALIPHATIC
HYDROCARBON FUELS

by

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An Experimental Investigation
of
The Sensitization of Aliphatic Hydrocarbon Fuels

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ABSTRACT

Jet aircraft fuels are relatively stable and safe to handle. Therefore they are not readily adaptable to weapons applications.

A study of the sensitization of the jet fuel with solid additives was carried out. Comparisons between the mixtures with the different solid additives were made to determine the best ones. An investigation of different ignition methods was also made to find a practical means of igniting the mixtures.

The results indicated that the jet fuel could be sensitized using a strong oxidizer in conjunction with either magnesium or red phosphorous. The fuel can also be ignited with a combination of chemicals which produce a spontaneous reaction.

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I. INTRODUCTION

Most of the fuels used in jet aircraft are 12 to 16 atom chain unsaturated hydrocarbons. These fuels are very stable and reasonably safe to handle. These characteristics are desirable from the standpoint of safety. However, for some weapons and other auxiliary applications it is desirable to have a fuel which ignites easily and burns readily. Rather than supply another fuel for these secondary uses, it would be desirable to modify the basic aircraft fuel so that it could also be used for weapons applications.

Researchers for the U. S. Naval Ordnance Test Station have found that the ignitability of the jet fuel could be significantly improved by the addition of 5% to 10% of volatile organic liquids [Refs. 1 and 2]. However, this method still requires the user to maintain a supply of the volatile liquid.

The purpose of this research was to investigate the possibility of sensitizing the jet fuel with dry chemicals. Ideally, these powdered or crystalline additives should dissolve in or be suspended in the fuel so that an isotropic substance would be formed.

For this research JP-5 was selected as the test fuel since it is a widely used and typical jet fuel. Popovich and Hering [Ref. 3] describe it as a specially fractionated kerosene having a higher flash point and lower freezing point than most kerosenes. Unless specified, all tests were conducted on the fuel which had been

solidified into a jelly-like substance by adding 10% thickener. The thickener used was a coprecipitate aluminum soap of oleic, napthenic and coconut fatty acids.

The investigation of the problem was entirely experimental. Since there has been little work done in this field, there were no standardized experimental procedures to follow. Therefore, methods for testing the sensitivity of the fuel mixtures were developed. In addition, the means of simulating an actual weapon do not exist. Consequently, it is impossible to determine if a particular fuel mixture is suitable for weapons' applications without a full scale test. The goal of this research was to find the additives which had the best probability of making the fuel useable.

II. EXPERIMENTATION

The experimental research was divided into three parts: (1) the initial qualitative tests, (2) the comparative tests, and (3) the simulation tests. Crystalline additives were pulverized prior to their use.

A. INITIAL QUALITATIVE TESTS

The initial tests were conducted to determine possible types of additives which might be used to sensitize the jet fuel. It was postulated that if the kerosene absorbed energy readily in a certain bandwidth, an additive which emitted in that same bandwidth would aid in the total ignition of the fuel. In order to determine if the fuel did absorb any narrow bandwidth of frequencies, a spectroscopic analysis of the JP-5 was made. The infra-red analysis was made using a Perkin-Elmer Infracord Spectrophotometer. The visible and ultra-violet analysis was made using a Beckman D B Spectrophotometer. In each case the analysis was made on a sample of the ungelled fuel with no chemicals or solvents added.

Other tests which consisted of simply trying different chemicals as additives were made. The additive was first mixed with the kerosene to determine if it would dissolve in the fuel. Then standard M-2 thickener was added and the mixture was allowed to gel. If the additive precipitated out of the mixture, it was thoroughly mixed after it had gelled. Then the mixture was burned. The ease of ignition, violence of the reaction, and flame spread characteristics were noted qualitatively. The first tests were performed on samples

gelled gasoline and gelled JP-5 without any additives. These tests provided a set of standards for further tests. Among the additives which were tested were explosives, pyrotechnics, oxidizers, and other very reactive substances.

B. COMPARATIVE TESTS

The previous testing determined possible additives which appeared to improve the flammability of the kerosene. In order to compare the effects of these additives, four comparison tests were developed.

1. Ignition Temperature

The first test was the measurement of the ignition temperature. Since the gelled fuel can be classified as either a liquid or a solid, some means of measuring its ignition sensitivity was needed.

This method of measuring the ignition temperature was chosen instead of the usual determination of the flash point since it measures the effect of the solid additives. As reported in Ref. 2, dusts of inorganic oxidizers suppress the ignition of hydrocarbon vapors. However, it is conceivable that some mixture might exist which would be sensitive to a small amount of heat. This method of determining the ignition temperature was suitable for measuring this type of sensitivity.

The equipment used in this test consisted of a nichrome wire, 0.82 mm in diameter, which was connected to a variable current power supply. This nichrome heating element was mounted on a movable wand. A chromel/alumel thermocouple, made from 0.305 mm wire, was spot welded to the center of the heating element. The thermocouple wires were connected to the lead wires in a cold bath at 0°C. The

thermocouple output was displayed as a function of time on a Fisher Recordall. A circuit diagram and a picture of the apparatus are shown in Figs. 1 and 2 respectively.

To perform the test the heating wire was placed against the surface of the gel and the current in the wire was gradually increased. It is important to note that the wire was placed on the gel so that the thermocouple junction bisected the part of the wire which was in contact with the gel. As the current was increased, the temperature of the wire was recorded as a function of time. At ignition the slope of the temperature/time curve increased if the flame temperature was greater than the ignition temperature. This discontinuity in the slope enabled the researcher to accurately determine the temperature of the heating element at ignition.

This experiment was found to have some inherent errors. Thirty-two different tests performed on samples of the gelled kerosene resulted in an average value of 895°C . The maximum deviation from this average temperature was about 9% using the absolute temperature. One factor which caused a significant error was the current feed through from the heating circuit to the thermocouple circuit. The mechanism of the feed through was not understood since the thermocouple circuit was connected to the heating circuit at only one point. However, a plot of temperature versus current indicated a dependence on the polarity of the heating circuit. A typical temperature/current graph is shown in Fig. 3. The dashed lines indicate the curves for each polarity of the basic circuit. The solid line is the average value. The graph indicates that the magnitude of the error is relatively small below about 600°C .

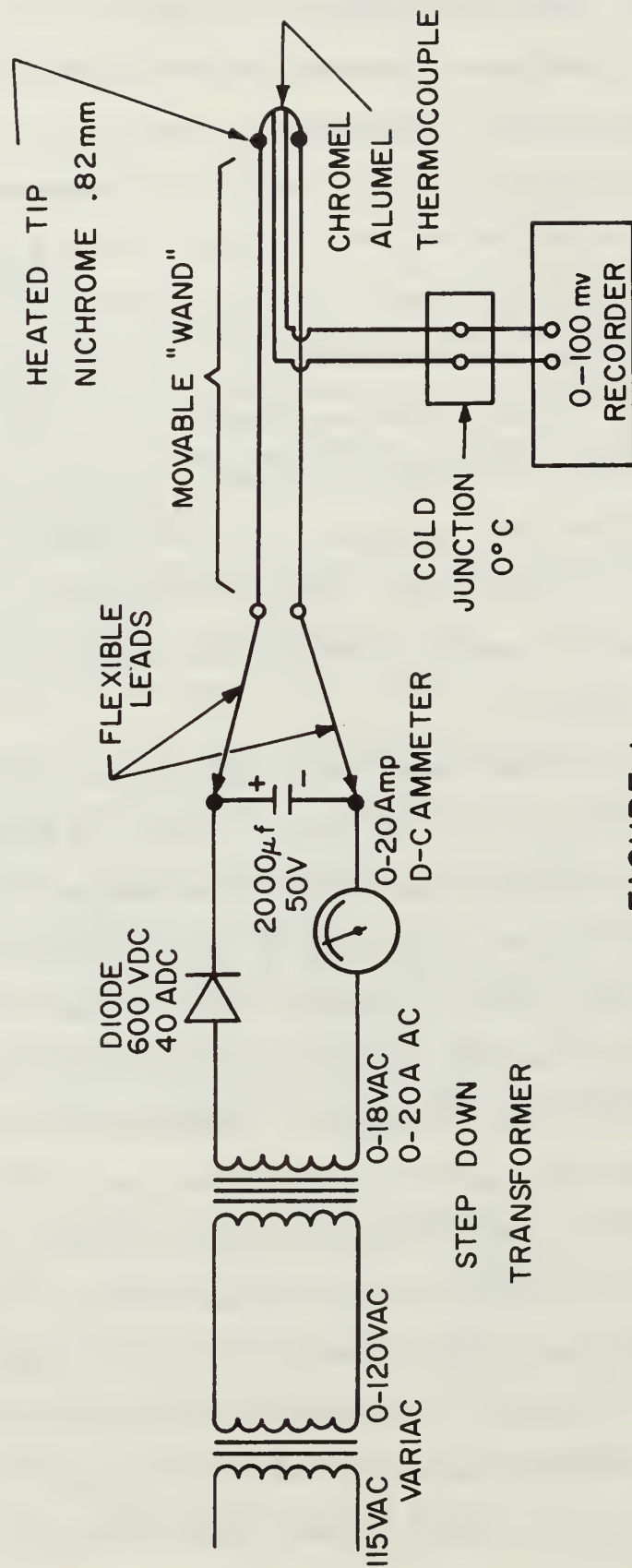


FIGURE 1

CIRCUIT DIAGRAM FOR TEMPERATURE MEASURING IGNITER

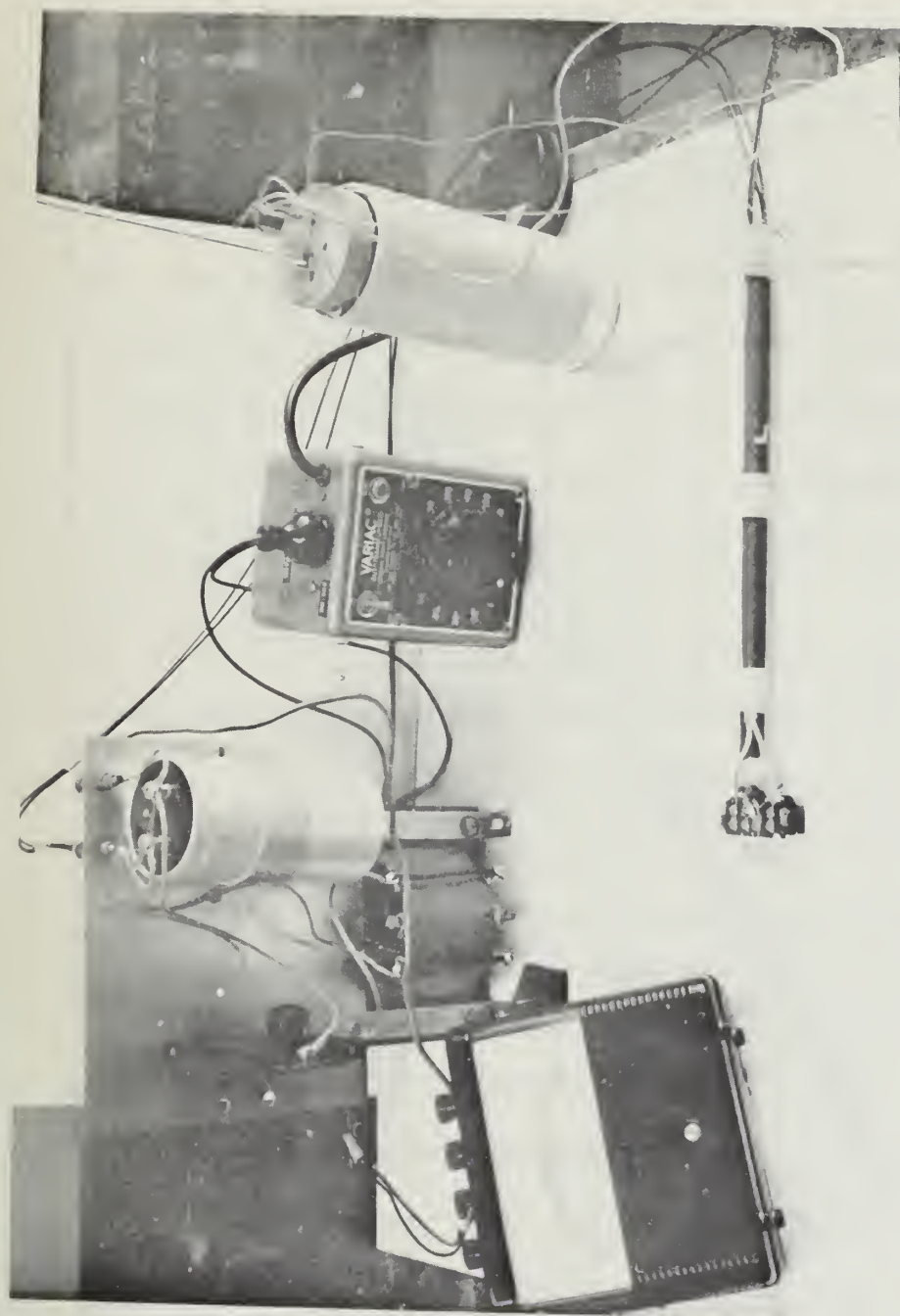


FIGURE 2
Illustration of Temperature Measuring Igniter

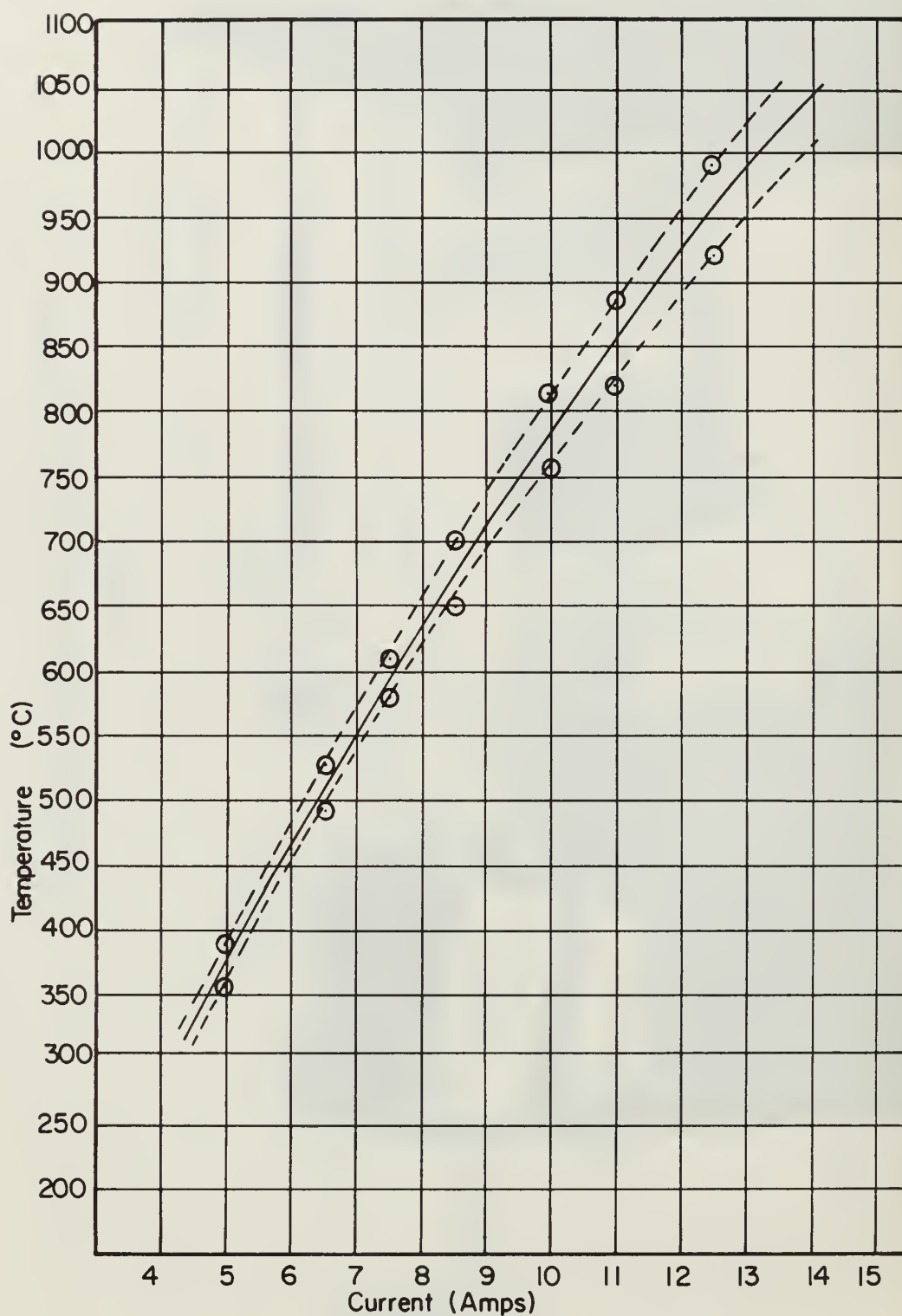


FIGURE 3
THE EFFECT OF A CHANGE IN POLARITY OF THE
HEATING ELEMENT

To overcome this difficulty the heating element circuit was modified so that the current was AC. The modified circuit is depicted in Fig. 4. Using this modified igniter, fifteen tests were made on samples of the basic fuel. The average ignition temperature was 875°C and the maximum deviation was less than 4.5%.

Another source of error was the amount of air circulating over the sample during the test. Increased air circulation caused the ignition temperature to be decreased. To eliminate this source of error, all ignition tests were conducted in an enclosed burning hood which had a quiescent atmosphere. After ignition had occurred, the exhaust fan was turned on.

In non-isotropic mixtures the ignition temperature varied up to 30% from the average value. These variations were probably due to microscopic variations in the composition of the mixture which was next to the heating element. To overcome possible errors due to this phenomenon, at least three tests were performed on each test mixture and the average of the three tests was recorded. In cases where there was a wide variation in the three readings, two more tests were performed to obtain a wider sample size.

2. Flame Transfer Distance

The second test developed was the measurement of the maximum distance at which a 5 ml sample of the gel would ignite a similar quantity of the gel. To perform this test the mixture, which was partially gelled, was poured into plastic cups, each having a capacity of 5 ml. When the mixture had become firm, the contents of the cups were unmolded onto small pieces of tinfoil about 4 cm square. These pieces of tinfoil were then arranged on a strip of

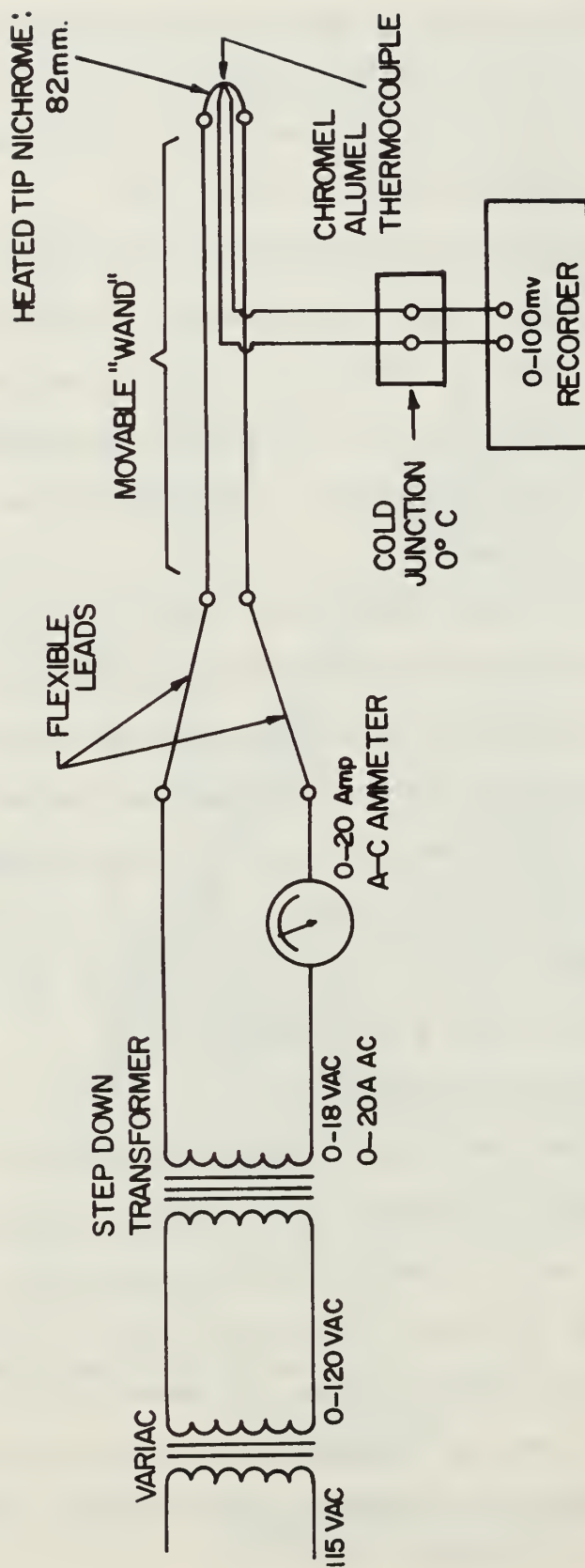


FIGURE 4

CIRCUIT DIAGRAM FOR ALTERNATE TEMPERATURE MEASURING IGNITER

asbestos tape as shown in Fig. 5. The distance between the centers of the molds was graduated in 1 cm increments. The purpose of the asbestos tape was to prevent any heat conduction between samples. From repeated tests on the same mixture, it was found that the maximum flame transfer distance, measured in this way, was accurate to within 1 cm. In all cases, the test was made at least twice. If the distance measured in each test was the same, that distance was recorded. If the distances were different, then the average of the two distances was recorded. During these tests, as soon as one of the fuel molds was ignited, the previous mold which was burning was removed from the vicinity of the test. This was done to prevent it from influencing the results with the additional heat which it radiated. This test was performed in a quiescent atmosphere also.

3. Surface Temperature

The third test developed was the measurement of the surface temperature under the burning sample. The equipment for this test consisted of a block of asbestos material with a chromel/alumel thermocouple mounted on it. The thermocouple was flush with the surface of the block. To perform the test, approximately 1-2 ml of the gel was placed on top of the thermocouple. The sample of the mixture was burned and the thermocouple output was recorded on the Fisher Recordall. After each test, the thermocouple was removed and the residue and ash from the burned sample was cleaned away.

For isotropic samples, like gasoline or kerosene, the test was reproducible to within 4%. For non-isotropic mixtures, the results of repeated tests varied up to 50%. This discrepancy in the results was probably caused by the non-homogeneity of the mixture and the consequent

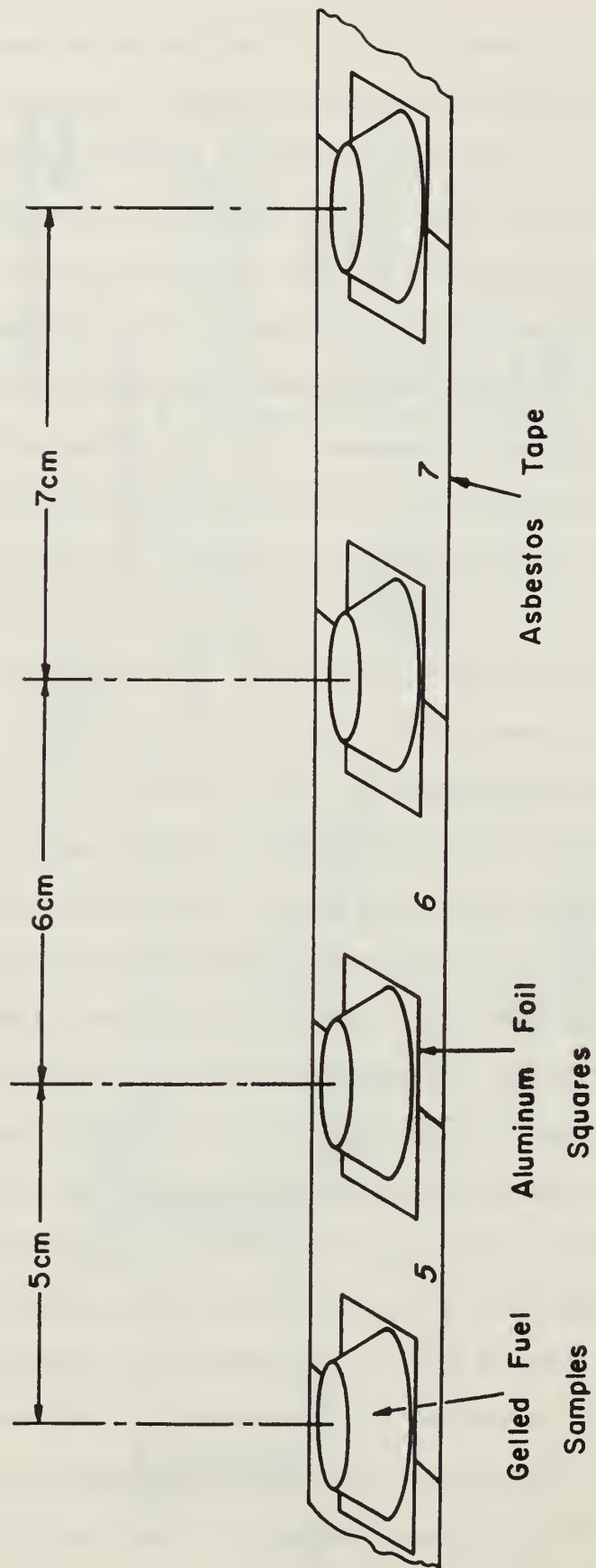


FIGURE 5

METHOD OF FLAME TRANSFER MEASUREMENT

uneven burning properties. To overcome this difficulty, the test was repeated three times on each mixture and the maximum temperature of the three readings was recorded. It should be noted that the two highest readings were generally within 10% of each other.

4. Flame Propagation Rate

The fourth test was the measurement of the flame propagation rate. This test was performed by burning a sample of the test mixture in a V-shaped trough. The trough was marked at 10 cm intervals. The time required for the flame front to travel from one mark to the next was measured with a stop clock. This test was found to be inaccurate. Three tests, performed on a sample of gelled kerosene, resulted in times of 27 sec, 43 sec, and 52 sec respectively. Apparently the rate of flame propagation was dependent on the consistency of the gel and the way it was distributed in the trough. The test did indicate the order of magnitude of the flame speed however.

5. Additional Tests

During the initial investigations, a method of igniting the gelled kerosene by a spontaneous reaction was discovered. The reaction was triggered by the addition of concentrated sulfuric acid. As a gauge of the spontaneity of the reaction, the time required for the reaction to take place was measured. To perform the test, approximately 5 to 10 ml of the gelled mixture was spread in the bottom of an aluminum dish. Then 1 ml of the acid was added. The time between the addition of the acid and ignition of the sample was measured with a stop clock. It was found that the speed of ignition was dependent on the amount of gel surface which was exposed to the acid. Mixing the acid into the gel did speed up the

reaction. To reduce this error, care was exercised in spreading the gel in the dish so that it was distributed uniformly. When the acid was added, it also was distributed uniformly over the surface of the gel.

One other test to measure the ignition sensitivity of a mixture was devised. In this test, the mixture was ignited by means of radiant energy from a standardized heat source. It was determined that this test was ineffective since the amount of heat required for ignition varied with the thickness of the gel sample being radiated.

C. SIMULATION TESTS

The simulation tests were conducted in an attempt to determine the adaptability of the mixtures to weapons applications. Since facilities for full-scale testing were not available, miniature firebombs were constructed and used in these tests.

The first series of tests was made to determine if the mixture could be ignited inside a closed container. To perform the test an initiator and the test mixture were sealed inside a thick-walled cylindrical glass container. The initiator was detonated and the results observed. The mixture used in these tests contained 5% red phosphorous and 10% potassium chlorate combined with the basic fuel gel. This mixture was selected since it had the lowest ignition temperature.

The second series of tests was performed using the same mixture. However, the container used was a thin-walled spherical glass one. The purpose of these tests was to determine if the mixture could be

ignited by a charge which also burst the container and spread the fuel mixture. The test was performed by sealing the charge and the fuel mixture in the container and initiating it.

The third series of tests involved the sugar/chlorate/sulfuric acid system. The fuel mixture, containing the sugar and chlorate, was placed in the thick-walled glass containers used in the previous tests. A test tube, containing 5 ml of concentrated sulfuric acid and covered with a piece of paper, was placed upright in the container. The container was then sealed. The container was tipped over so that the acid disintegrated the paper and reacted with the fuel mixture. When the reaction had reached the stage that smoke and possibly even flames were present, the container was dropped from a height of 10 feet onto a steel plate. The purpose of this series of tests was to determine if the entire contents would be ignited as the container broke and the contents splashed out. The results of these tests were photographed using a Kodak high speed camera. Pictures were taken at a speed of approximately 500 frames per second.

III. RESULTS

A. INITIAL INVESTIGATIONS

The spectroscopic analysis showed that the basic fuel did not absorb any particular frequencies in the ultra-violet or visible spectra. In the infra-red range it absorbed energy at 3.4 microns, 6.9 microns, and at 7.4 microns. The results of the infra-red spectroscopic analysis are contained in Fig. 6.

Although devices can be built which emit energy at particular frequencies in the infra-red range, none of them are very simple. No simple additive was found which would emit energy at the infra-red frequencies of interest. Therefore, it was deemed impractical to use some form of single frequency energy emitter as an igniter for the fuel.

A wide variety of chemicals were tried to see if any would improve the inflammability of the kerosene. The following additives were mixed with the fuel gel but did not noticeably improve its burning characteristics:

Cellulose Nitrate

Holox #1 (a pyrotechnic)

Potassium Dichromate

Ammonium Dichromate

Copper Sulfate

Sugar

Magnesium Teflon Pyrotechnic

Calcium Hypo-Chlorite

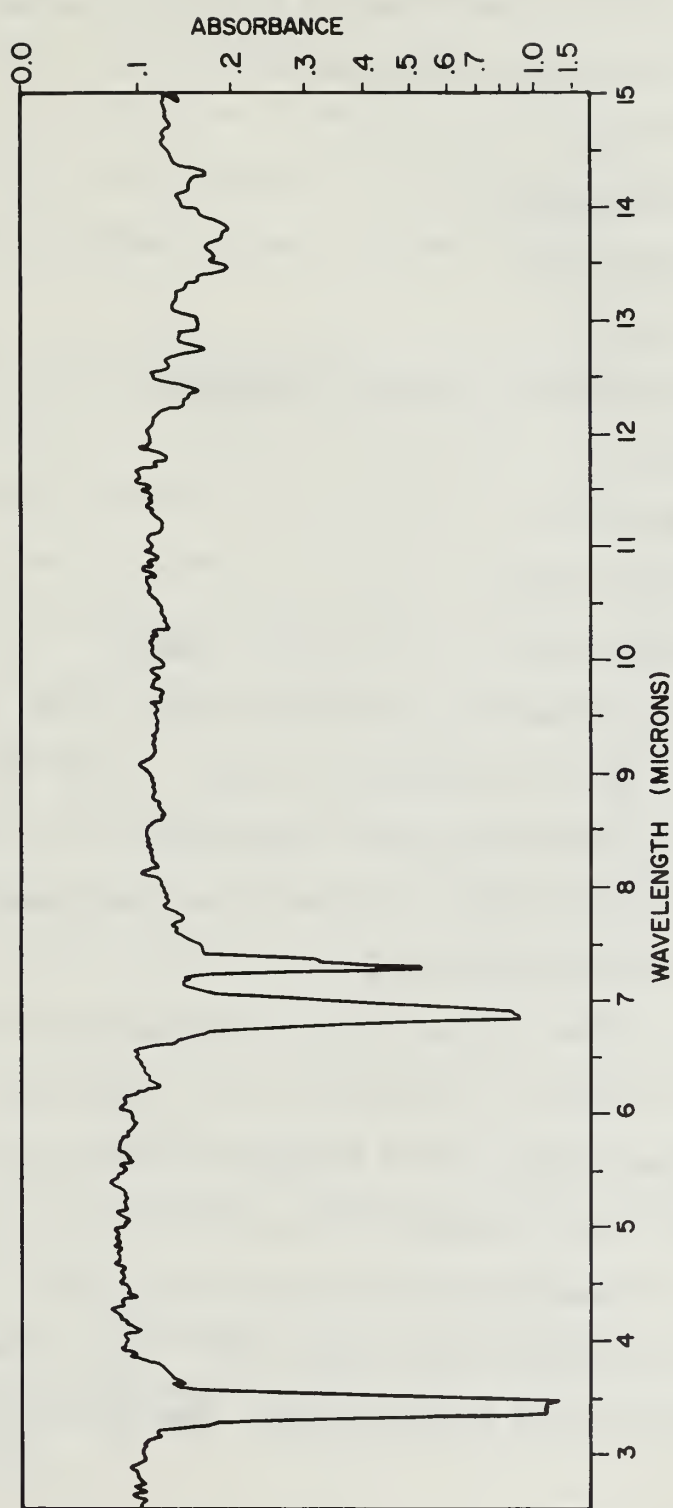


FIGURE 6

RESULTS OF THE INFRA-RED SPECTROSCOPIC ANALYSIS OF JP-5

Calcium Hypo-Chlorite and Tannic Acid

Zirconium and Carbon Tetrachloride

Calcium Hypo-Chlorite and Alcohol

The following chemicals, which are all good oxidizers, were selected for further testing because they appeared to improve the flammability of the basic fuel gel:

Potassium Permanganate

Ammonium Perchlorate

Hydrogen Peroxide

Hydrogen Peroxide and Potassium Dichromate

Sodium Chlorate

Potassium Chlorate

Potassium Perchlorate

This selection was based on a qualitative judgment.

Tests were performed using cellulose nitrate in two different forms: (1) as a solid, and (2) dissolved in acetone. In the first test the cellulose nitrate would not remain in suspension in the liquid. In the second case it precipitated out as the acetone evaporated from the liquid fuel and acetone solution.

Like the cellulose nitrate, none of the other solid chemicals would dissolve or remain in suspension in the liquid fuel. However, once the fuel had gelled, all of the chemicals would remain in suspension after being thoroughly mixed with the gel. It was found that if any solid chemical was first mixed with an equal volume of Cab-O-Sil and then added to the liquid fuel it would precipitate out only slightly during the gelling process. The Cab-O-Sil is a very

finely divided silica gel. It has a low density and therefore it would contribute little excess weight to the total mixture.

The hydrogen peroxide was tested qualitatively even though it is a liquid. It did not dissolve in nor form an emulsion with the fuel. However, the gel did appear to be more readily ignitable after it had been mixed with hydrogen peroxide and the excess liquid drained off. Apparently some oxygen had been absorbed by the fuel gel when it was mixed.

Besides using the additives mentioned, another test was performed in an attempt to find a means of igniting the fuel. A solution of carbon disulfide and white phosphorous was spread over the surface of the gel. It was anticipated that when the carbon disulfide evaporated, the white phosphorous would ignite and, in turn, ignite the basic fuel. This chain of events did not take place. Instead, as the carbon disulfide evaporated, some of the phosphorous oxidized and produced a white smoke. Most of it was coated with the fuel, however, and therefore did not react. Since this fuel does not readily evaporate, the amount of white phosphorous which oxidized was insufficient to produce the heat necessary for ignition of the fuel.

During this portion of the investigation, a method of spontaneously igniting the fuel mixture by adding a small quantity of concentrated sulfuric acid was discovered. The mixtures which could be ignited in such a manner were:

- (1) Fuel gel, 10% sodium chlorate, and 10% sugar
- (2) Fuel gel, 10% sodium chlorate, 5% arsenious oxide, and 5% sulfur.

Potassium chlorate could be substituted for the sodium chlorate in these mixtures. Investigation also showed that the sulfuric acid would not ignite the gel if either the chlorate or the sugar/sulfur were omitted from the mixture.

B. COMPARATIVE TESTS

The first comparative tests were made using an oxidizer and a second highly reactive chemical. The oxidizers used in these tests were those selected for further testing during the initial investigations. In these tests the ignition temperature of the mixtures, which contained the various chemical pairs, was measured. The first mixtures contained 10% potassium chlorate and a second chemical as shown in Table I. The second mixtures contained 6% red phosphorous and an oxidizer as shown in Table II. The purpose of these tests was to determine the combinations of chemical and oxidizer which would probably yield the greatest reduction of the ignition temperature. From these tests the oxidizers, which were selected for further testing, were sodium chlorate, potassium chlorate, ammonium perchlorate, potassium perchlorate, and sodium peroxide. The chemicals, which were used in conjunction with the oxidizers and which were selected for further study, were magnesium and red phosphorous.

In addition to the chemical combinations, other additives and combinations of additives were tested to determine how effectively they improved the inflammability of the basic kerosene gel. A listing of the mixtures used and their test results are given in Table III. Included in this listing are the test results for gelled

TABLE I

IGNITION TEMPERATURE MEASUREMENTS

Compound Added to Mixture of Gelled Fuel and 10% KClO_3	Ignition Temperature ($^{\circ}\text{C}$)
None	580
Magnesium	340
Sulfur	550
Thermit	625
Silicone	805
Carborondum	820
Manganese	750
Red Phosphorous	335
Alumina	390
Aluminum (powdered)	855

TABLE II

IGNITION TEMPERATURE MEASUREMENTS

Oxidizer Added to Mixture of 6% Red Phosphorous and Gelled Fuel	Ignition Temperature ($^{\circ}\text{C}$)
None	780
Sodium Chlorate	250
Potassium Chlorate	280
Potassium Perchlorate	425
Ammonium Perchlorate	325
Benzoyl Peroxide	720
Potassium Permanganate	780
Sodium Peroxide	450

aviation gasoline, grade 115/145, and for gelled JP-5. These two test results provide a set of standards by which the other mixtures can be judged.

The ignition temperatures of JP-5 and the gasoline gels are essentially the same. This is not inconsistent with the known fact that gasoline is more flammable. This test indicates the fuel's sensitivity to heat. To determine the fuel which is most flammable, all the test results must be considered.

By studying the table it is apparent that all of the test mixtures have a much slower flame propagation rate than the gasoline gel. This is one desirable characteristic of the gasoline which could not be duplicated with any of the test mixtures. It is also apparent that the ignition temperature for most of the mixtures was lower than the ignition temperature of the gasoline. In this respect these tested mixtures are more sensitive than the gasoline gel. For the maximum flame transfer distance, Table III indicates that the mixtures containing magnesium and a perchlorate have a flame transfer distance which is almost equal to that of the gasoline. However, this indication may not be accurate. The gasoline sample used in these tests was gelled in an open container. During the gelling process, many of the more volatile components were allowed to escape. If the gasoline had been gelled in a closed container and then tested as soon as the container was opened, the flame transfer distance would probably have been slightly greater since the more volatile components, which would have been present in this case, would aid in the flame transfer. In the case of the kerosene mixtures, the primary means

TABLE III

TEST RESULTS FOR THICKENED FUEL
WITH VARIOUS ADDITIVES

Additive	Ign Temp (°C)	Surf Temp (°C)	Flame Trans (cm)	Flame Speed (cm/min)
Gasoline	875	450	9.5	2000*
JP-5	895	475	5	12
10% NaClO ₃	645	640	6.5	11
10% KClO ₃	730	510	6.5	12
10% NH ₄ ClO ₄	625	510	6.5	15
10% KClO ₄	575	755	7.5	15
10% NH ₄ NO ₃	915	470	5	8
10% KClO ₄ , 5% P	475	540	7	9
10% Na ₂ O ₂ , 5% P	440	450	5	15
10% KClO ₃ , 5% P	370	570	6.5	12
10% NH ₄ ClO ₄ , 5% P	440	485	7.5	10
10% NaClO ₃ , 5% P	280	540	7	13
5% Na ₂ O ₂ , 5%P	460	---	5	12
5% NH ₄ ClO ₄ , 5% NaClO ₃ , 5% P	310	460	6	9
10% NaClO ₃ , 5% Mg	425	650	8	11
10% KClO ₃ , 5% Mg	780	700	7	12
10% NH ₄ ClO ₄ , 5% Mg	525	590	9	9
10% KClO ₄ , 5% Mg	705	1050	8.5	10
10% NaClO ₃ , 5% Sugar	775	475	5.5	12
10% NaClO ₃ , 5% Sugar	645	400	6	12
10% NaClO ₃ , 5% Alumina (activated)	700	630	6.5	12

*This value is approximate

of flame transfer does not involve the volatile components and therefore gelling in an open container did not affect the maximum flame transfer distance.

A study of the test results shows that all of the test mixtures, except the ammonium nitrate mixture, have a lower ignition temperature than the gelled kerosene. The mixtures containing red phosphorous and an oxidizer generally have the lowest ignition temperatures. The mixtures containing magnesium and an oxidizer exhibit higher surface temperatures and greater flame transfer distances.

Considering all of the measurements made, the flame speed and the flame transfer distance are probably the best indicators of flammability. The ignition temperature is an indicator of the fuel's sensitivity to heat. As such it can be considered as an indicator of either the mixture's handling safety or its flammability. The surface temperature is a measurement of the mixture's effectiveness as a weapon's fuel and not a direct measurement of its flammability.

Since the magnesium/oxidizer systems appear to exhibit the greatest flame transfer distances and the highest surface temperatures, tests were conducted on them to optimize the additive concentrations. The red phosphorous/ammonium perchlorate system was also studied since it had a relatively large flame transfer distance.

The results for the magnesium/potassium perchlorate system are contained in Table IV. Graphs showing the variation of the test results as a function of concentration are presented in Figs. 7, 8, 9, and 10. The points depicted on these curves are average values. The arrows on the ignition temperature and flame transfer distance curves indicate the range of the data points. The arrows

on the surface temperature curves indicate the range of the two highest readings. Where no arrows are shown, the point was reproducible to within the accuracy of the measuring device.

TABLE IV
TEST RESULTS FOR THE Mg/KClO₄ SYSTEM

Mixture	Ign Temp (°C)	Surf Temp (°C)	Flame Trans (cm)	Flame Speed (cm/min)
5% Mg, 5% KClO ₄	680	575	8	13
5% Mg, 7.5% KClO ₄	710	965	8.5	16
5% Mg, 10% KClO ₄	705	1050	8.5	11
5% Mg, 13% KClO ₄	650	1070	11	14
5% Mg, 15% KClO ₄	570	985	9	11
0% Mg, 10% KClO ₄	640	755	7.5	15
2.5% Mg, 10% KClO ₄	605	915	8	15
5% Mg, 10% KClO ₄	705	1050	8.5	11
7.5% Mg, 10% KClO ₄	590	980	11	12
6% Mg, 12% KClO ₄	650	1060	9.5	11

From this data, the best mixture would appear to contain 6% magnesium and 12% potassium perchlorate. The results for this particular mixture are also presented in Table IV. It should be noted that the maximum surface temperature and the flame transfer distance for this particular mixture are less than the corresponding values for a 5% magnesium and 13% potassium perchlorate mixture. Therefore, it was concluded that the optimum concentrations of the two additives could not be determined independently. For this reason, other systems were optimized with respect to the oxidizer

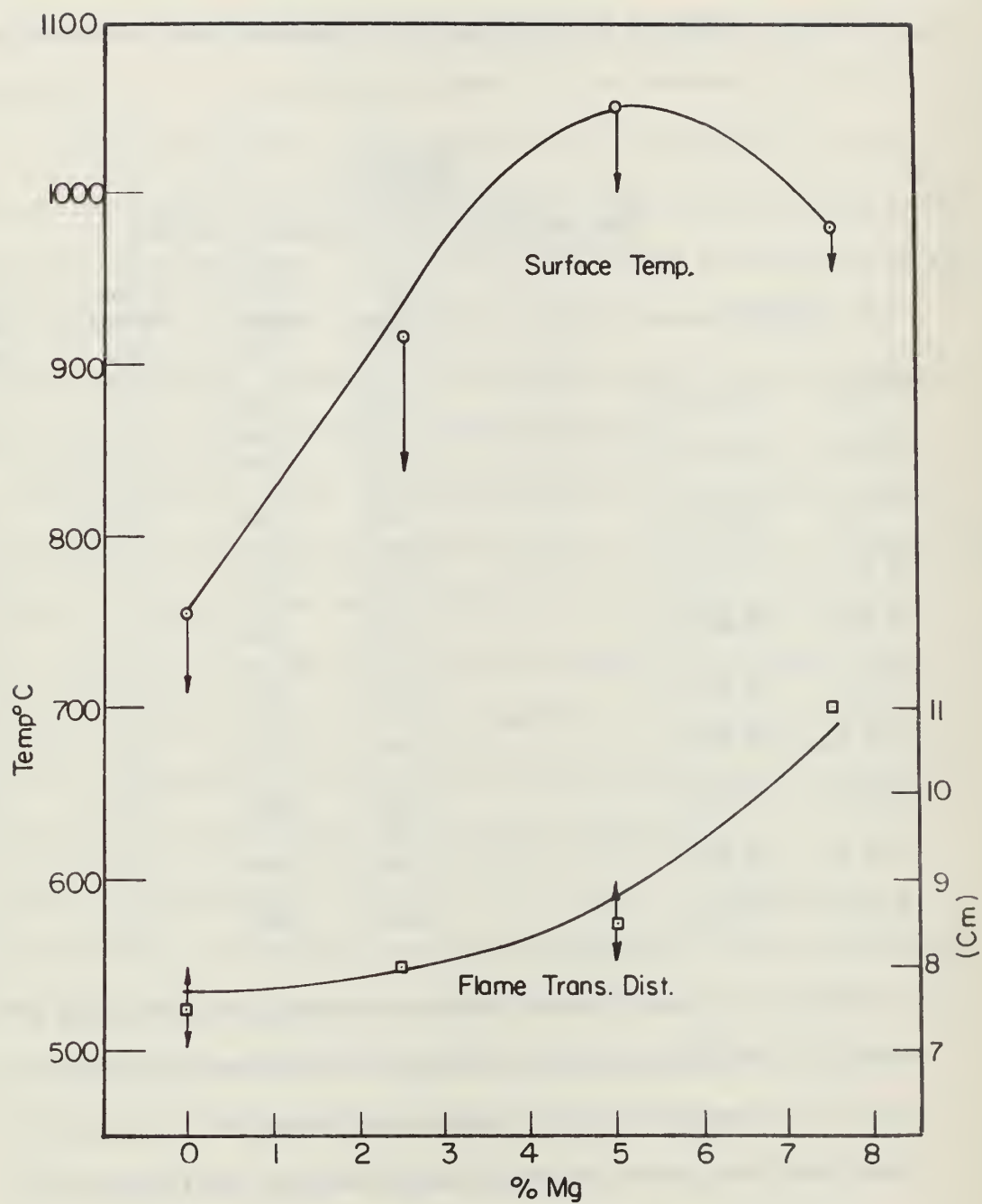


FIGURE 7

VARIATION OF TEST RESULTS FOR
A MIXTURE OF FUEL, 10% KClO_4
AND VARYING CONCENTRATIONS OF
Mg.

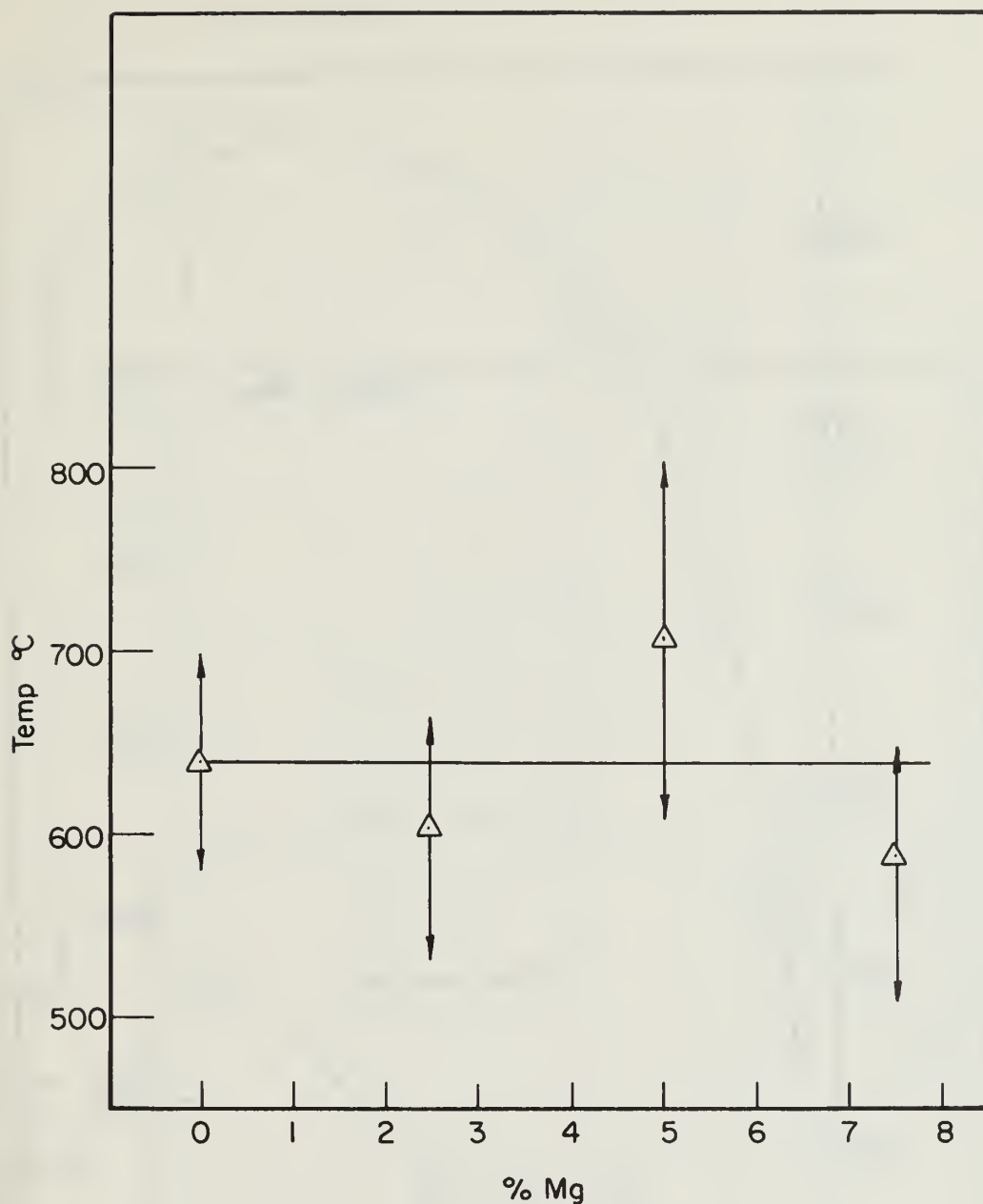


FIGURE 8
VARIATION OF IGNITION TEMPERATURE
FOR A MIXTURE OF FUEL, 10% KClO₄,
AND VARYING CONCENTRATIONS OF Mg.

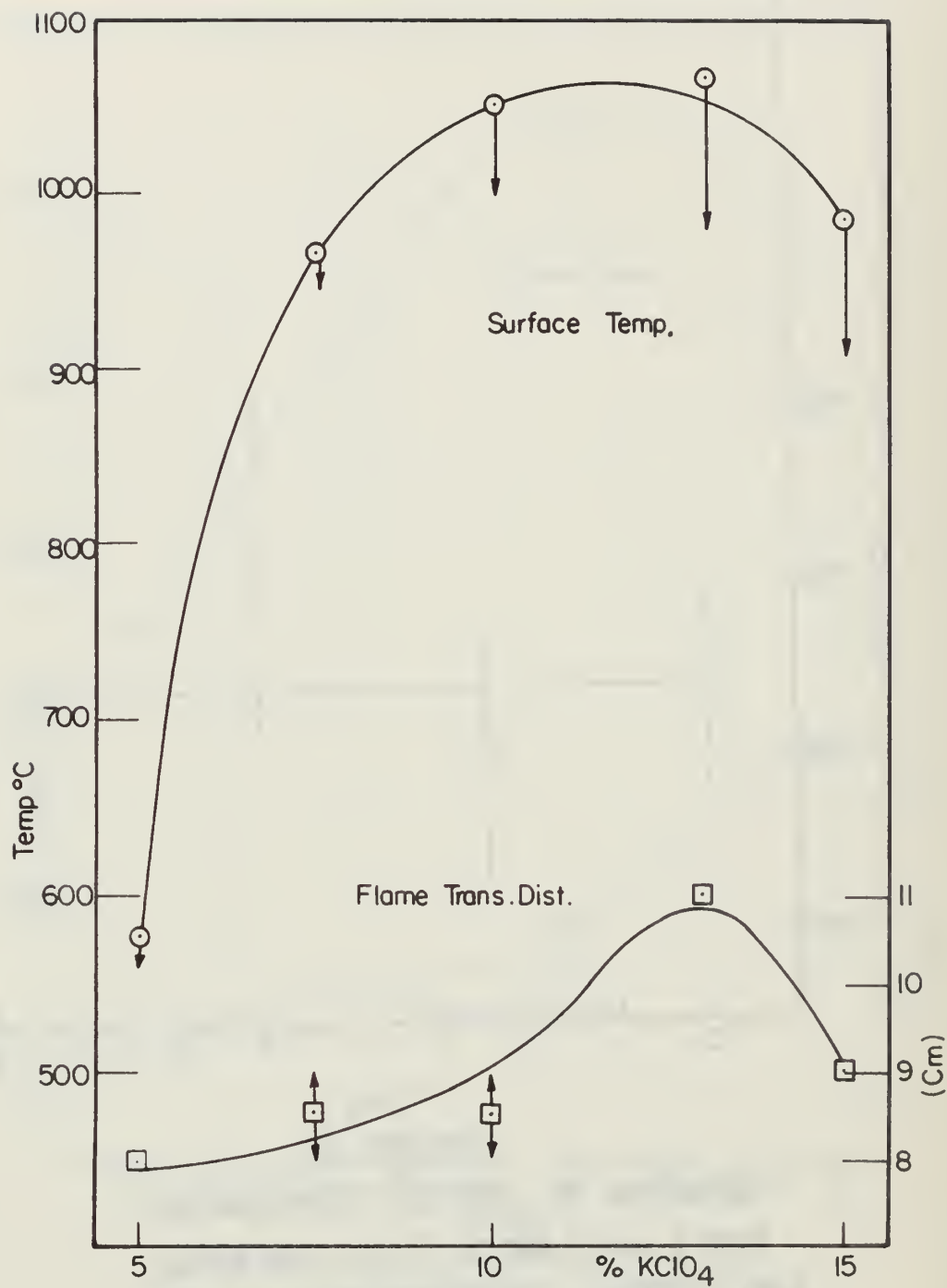


FIGURE 9

VARIATION OF TEST RESULTS FOR A
MIXTURE OF FUEL, 5% Mg, AND
VARYING CONCENTRATIONS OF KClO_4

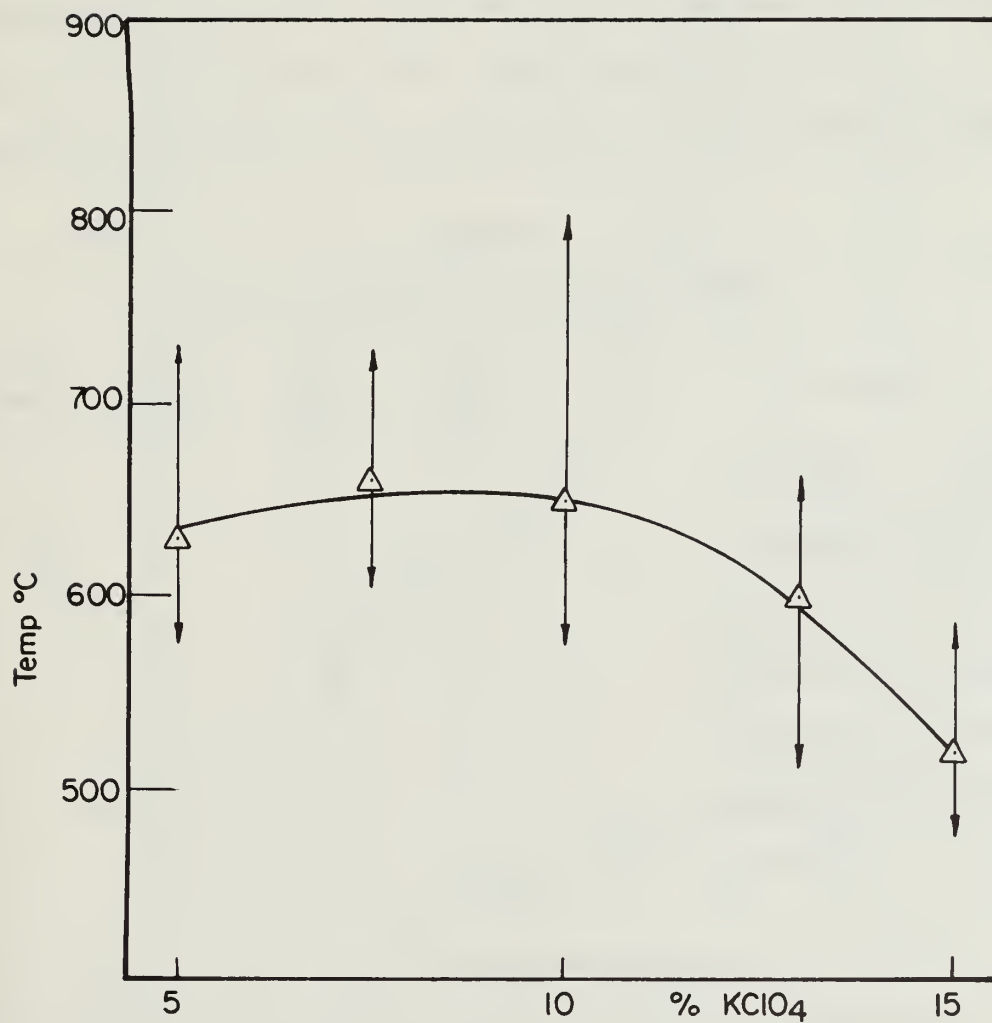


FIGURE 10

VARIATION OF IGNITION TEMPERATURE
FOR A MIXTURE OF FUEL, 5% Mg, AND
VARYING CONCENTRATIONS OF KClO₄

only. Since it is desirable to obtain the best results with a minimum amount of additives, the optimum concentrations for the magnesium/potassium perchlorate system was determined to be 5% magnesium and 10% potassium perchlorate.

The results for the magnesium/sodium chlorate system are contained in Table V and depicted graphically in Figs. 11 and 12. These results show that the mixture with the best compromise among the properties of low ignition temperature, large flame transfer distance, and high surface temperature contains 5% magnesium and 12.5% sodium chlorate.

TABLE V
TEST RESULTS FOR THE Mg/NaClO₃ SYSTEM

Mixture	Ign Temp (°C)	Surf Temp (°C)	Flame Trans (cm)	Flame Speed (cm/min)
5% Mg, 5% NaClO ₃	780	580	6.5	13
5% Mg, 7.5% NaClO ₃	735	625	8	12
5% Mg, 10% NaClO ₃	425	650	8	11
5% Mg, 12.5% NaClO ₃	585	720	8.5	13
5% Mg, 15% NaClO ₃	705	995	8	9
5% Mg, 17.5% NaClO ₃	790	665	8.5	13
5% Mg, 20% NaClO ₃	735	640	9.5	9

The results for the magnesium/potassium chlorate system are given in Table VI and Figs. 13 and 14. A mixture of 5% magnesium and 12.5% chlorate produced the best results.

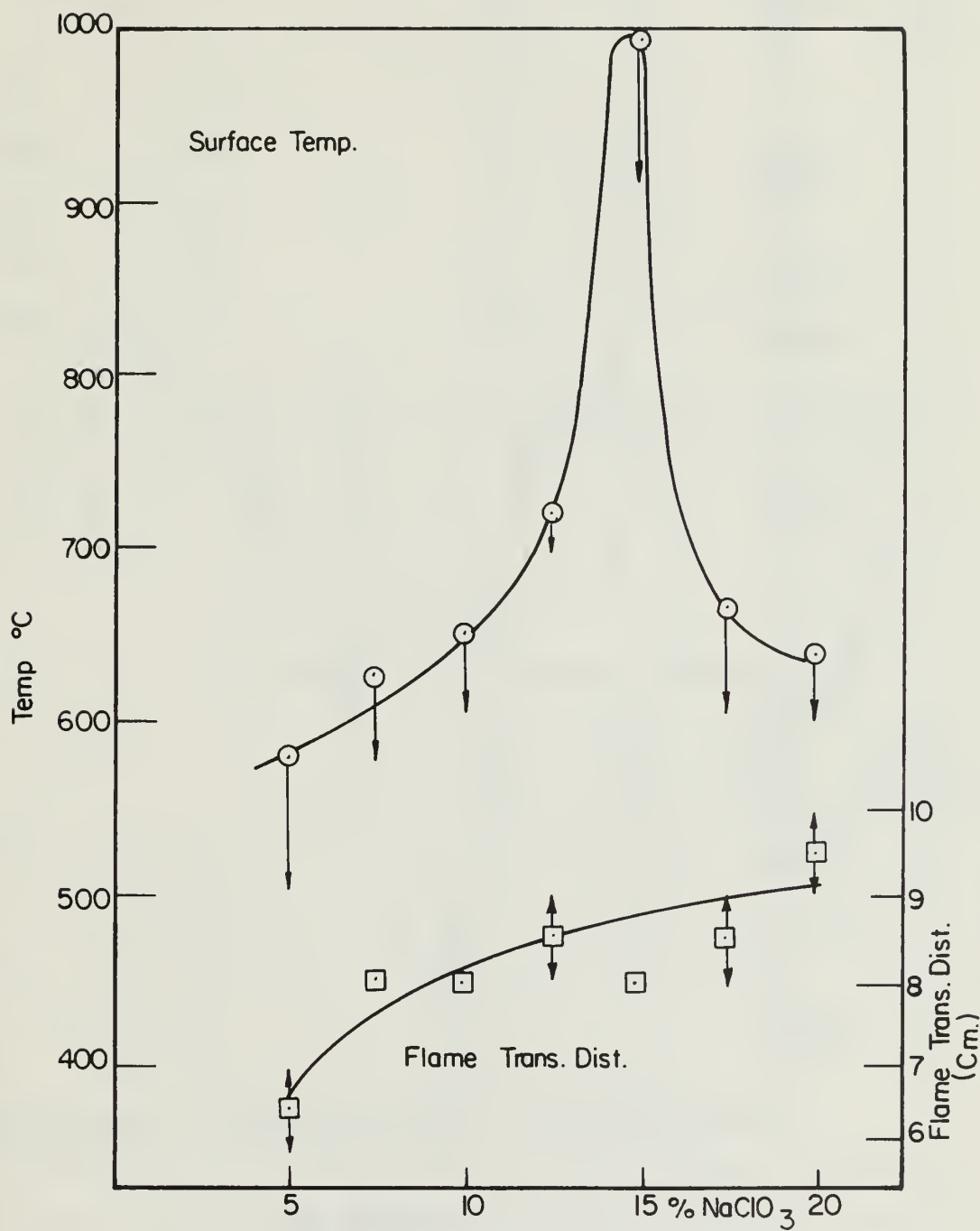


FIGURE 11
 VARIATION OF TEST RESULTS FOR A
 MIXTURE OF FUEL, 5% Mg, AND
 VARYING CONCENTRATIONS OF NaClO_3

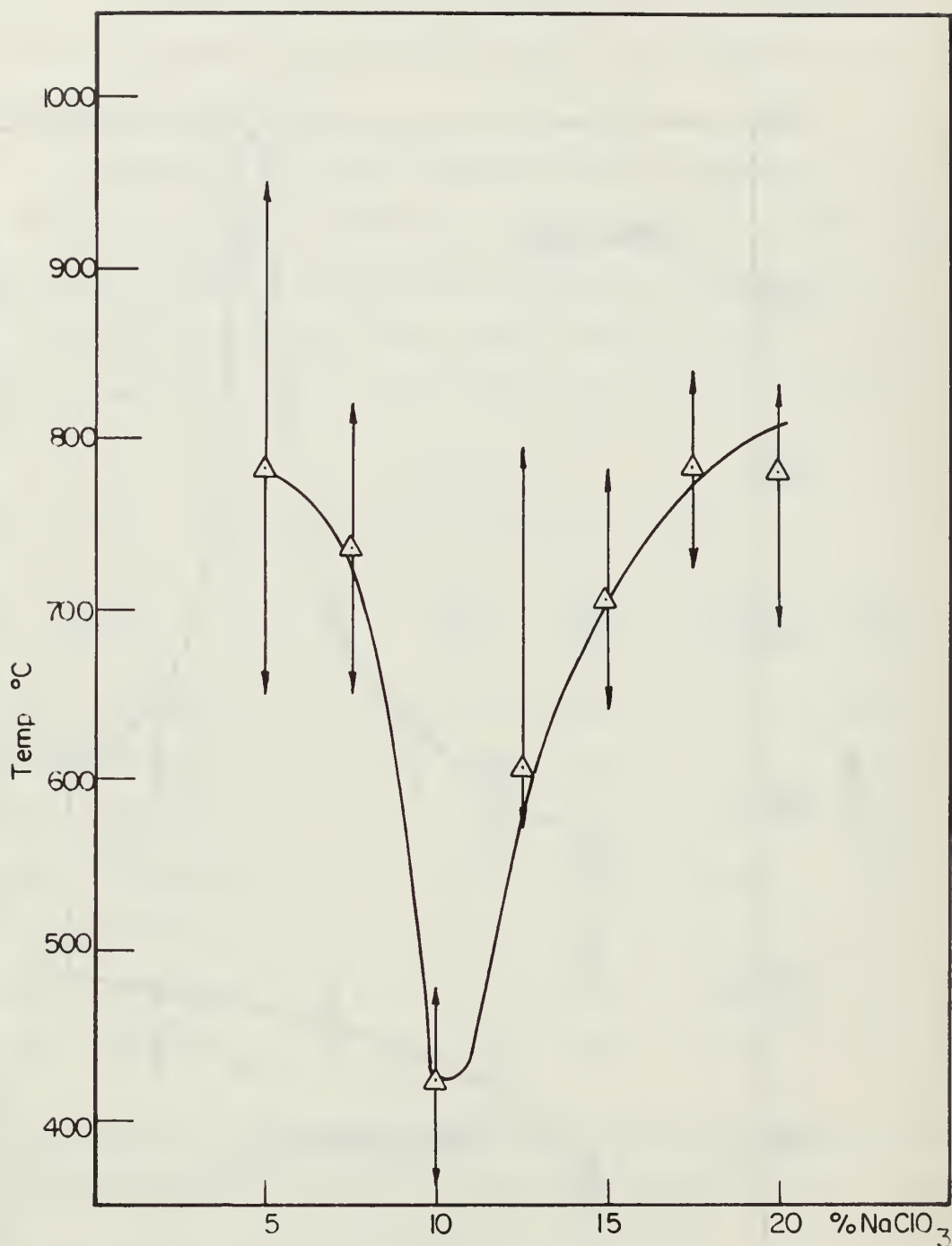


FIGURE 12

VARIATION OF IGNITION TEMPERATURE
FOR A MIXTURE OF FUEL ,5%Mg, AND
VARYING CONCENTRATIONS OF NaClO₃

TABLE VITEST RESULTS FOR THE Mg/KClO_3 SYSTEM

Mixture	Ign Temp (°C)	Surf Temp (°C)	Flame Trans (cm)	Flame Speed (cm/min)
5% Mg, 7.5% KClO_3	630	355	8	10
5% Mg, 10% KClO_3	780	580	8.5	12
5% Mg, 11% KClO_3	750	535	8.5	12
5% Mg, 12.5% KClO_3	615	625	8.5	12
5% Mg, 15% KClO_3	585	745	8	11

The test results for the red phosphorous/ammonium perchlorate system are shown in Table VII. A graphical representation of the results is given in Figs. 15 and 16.

TABLE VIITEST RESULTS FOR THE $\text{P/NH}_4\text{ClO}_4$ SYSTEM

Mixture	Ign Temp (°C)	Surf Temp (°C)	Flame Trans (cm)	Flame Speed (cm/min)
5% P, 5% NH_4ClO_4	455	330	6.5	11
5% P, 7.5% NH_4ClO_4	415	440	8	11
5% P, 10% NH_4ClO_4	425	485	7.5	10
5% P, 12.5% NH_4ClO_4	435	370	7.5	23
5% P, 15% NH_4ClO_4	390	385	7	13

During the initial investigations, it was determined that mixtures containing a chlorate and sugar could be ignited by adding concentrated sulfuric acid. Therefore, various combinations of these chemicals were tested to determine the combinations with the best properties. The

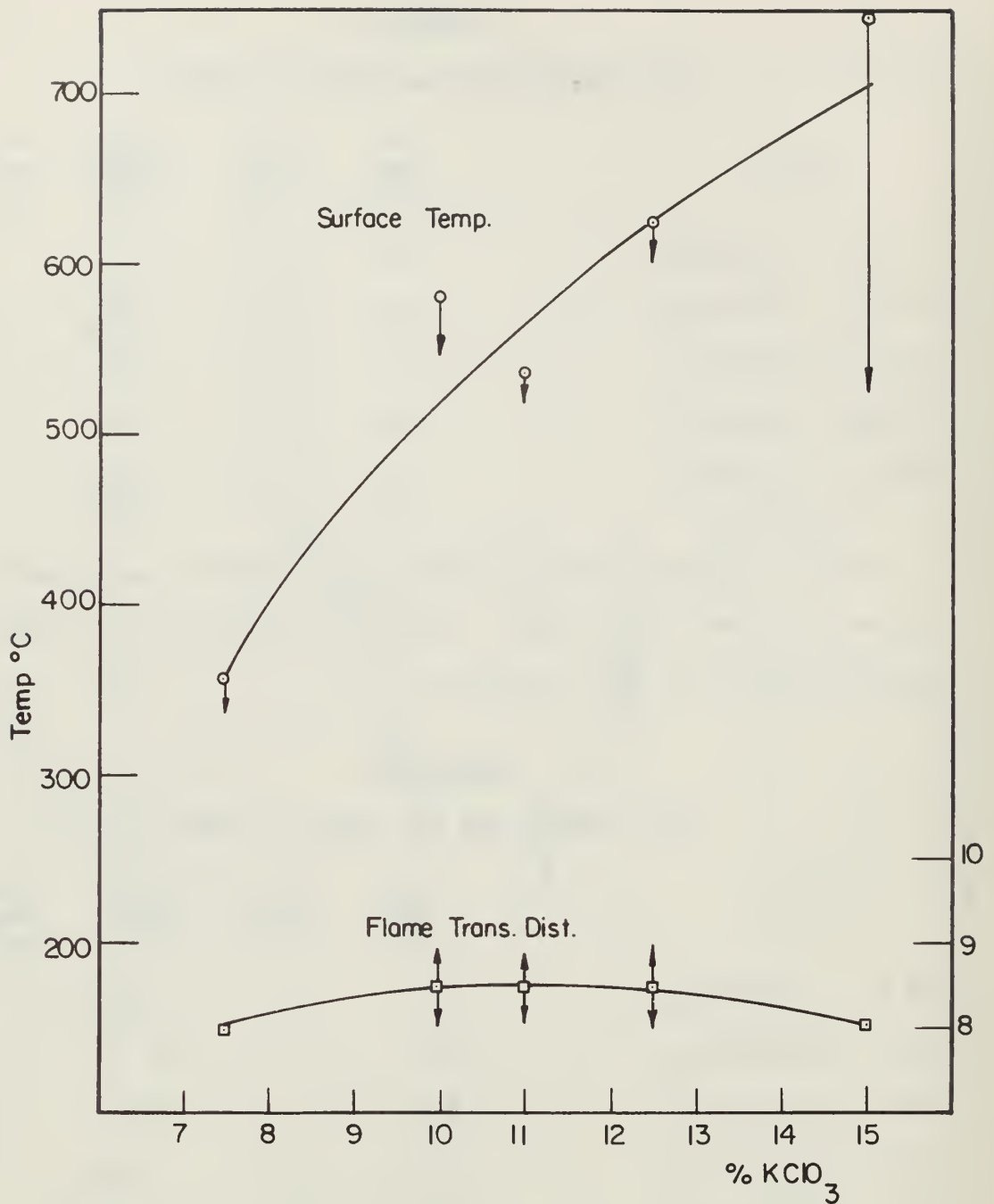


FIGURE 13

VARIATION OF TEST RESULT FOR A
MIXTURE OF FUEL, 5% Mg, AND
VARYING CONCENTRATIONS OF KClO_3

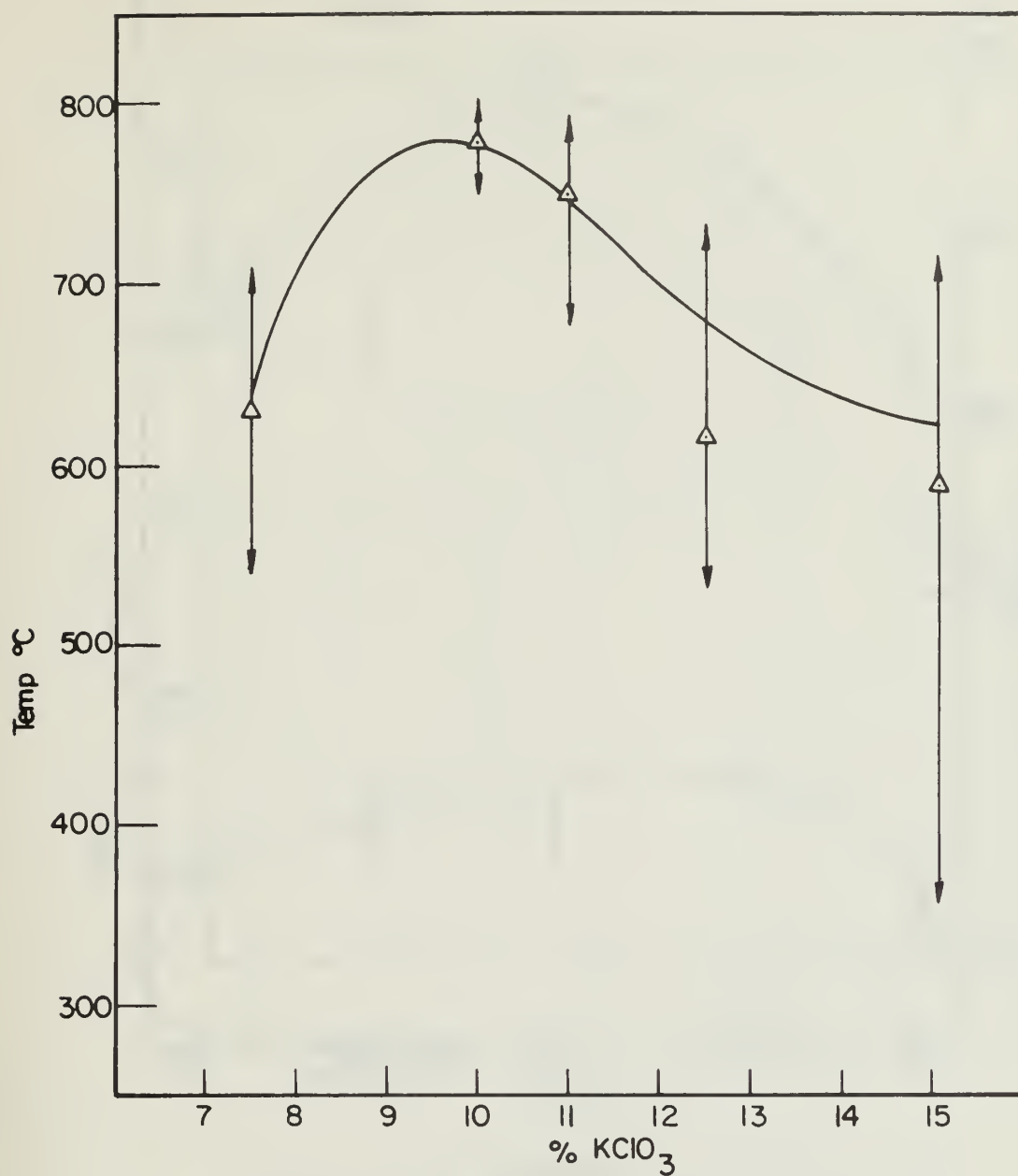


FIGURE 14

VARIATION OF IGNITION TEMPERATURE FOR
A MIXTURE OF FUEL, 5% Mg, AND VARYING
CONCENTRATIONS OF KClO₃

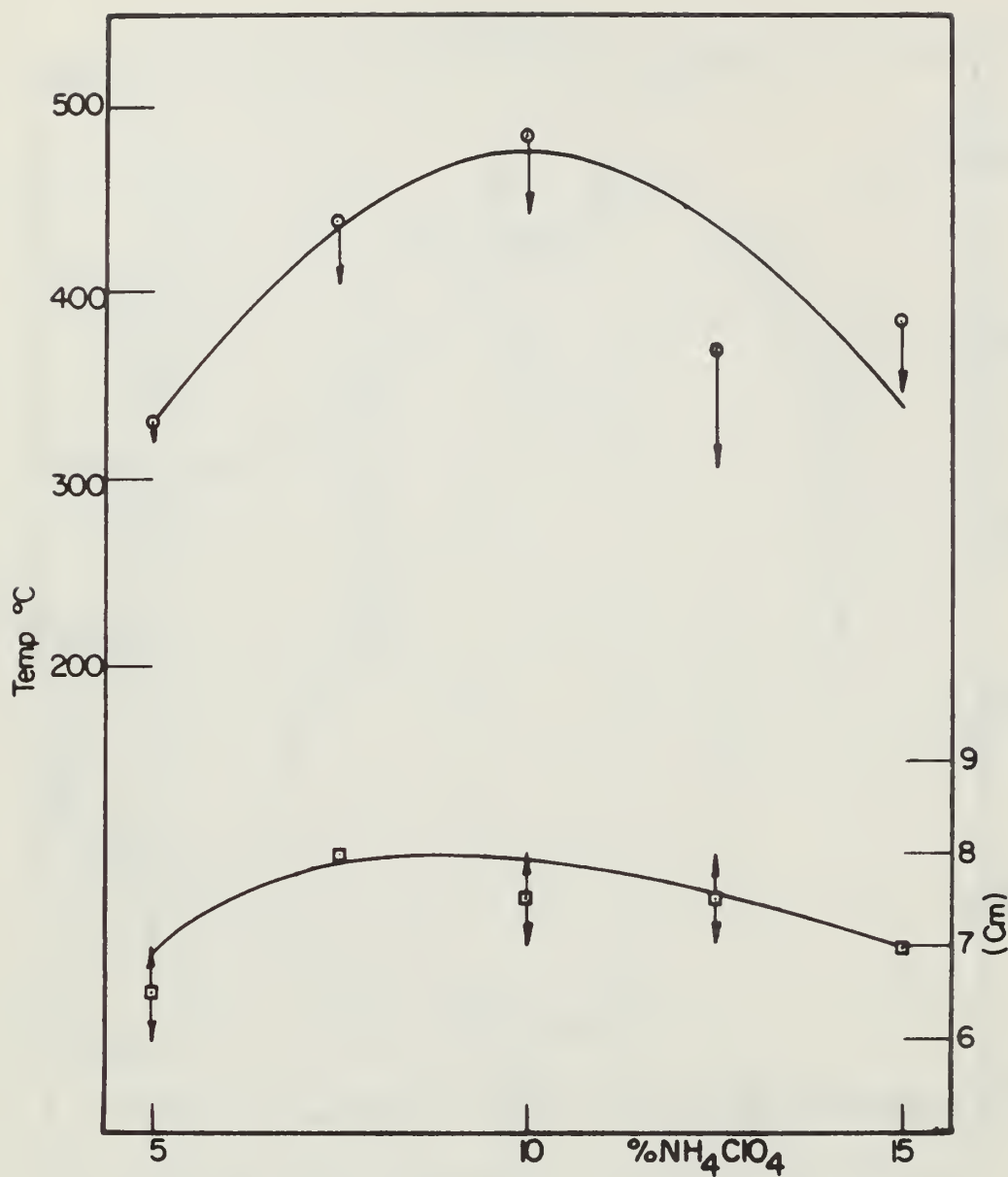


FIGURE 15

VARIATION OF TEST RESULTS FOR A
MIXTURE OF FUEL, 5% P, AND VARYING
CONCENTRATIONS OF NH₄ClO₄

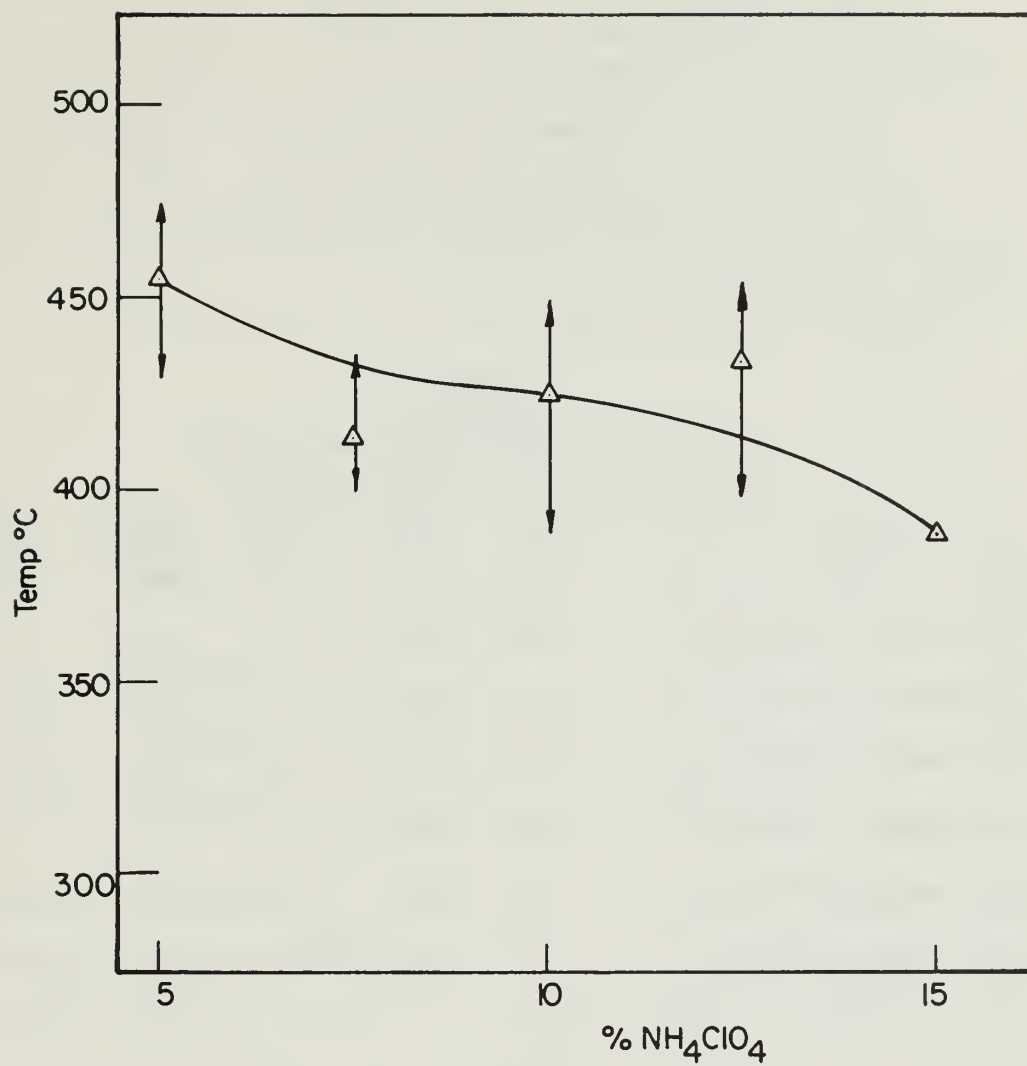


FIGURE 16

VARIATION OF IGNITION TEMPERATURE FOR
A MIXTURE OF FUEL , 5% P, AND VARYING
CONCENTRATIONS OF NH_4ClO_4

results are presented in Table VIII. The results show that the ignition time decreases as the chlorate concentration increases. It increases, however, when a third substance, like magnesium, is added. Apparently the potassium chlorate mixtures have a faster ignition time than the sodium chlorate mixtures. Considering all the tests, the best mixture contained 10% potassium chlorate, 5% magnesium and 2% sugar.

TABLE VIII

MIXTURES WHICH IGNITE SPONTANEOUSLY

Mixture	Ign Time (sec)	Ign Temp (°C)	Surf Temp (°C)	Flame Trans (cm)	Flame Speed (cm/min)
10% NaClO ₃ 5% Sugar	65	770	475	5.5	12
10% NaClO ₃ 7.5% Sugar	37	900	450	5	12
10% NaClO ₃ 10% Sugar	49	665	400	6	12
15% NaClO ₃ 5% Sugar	24	640	460	5	9
15% NaClO ₃ 2.5% Sugar	25	825	520	5	11
10% KClO ₃ 5% Mg 2% Sugar	25	525	535	7	15

The results indicate that the red phosphorous and chlorate systems have the lowest ignition temperatures. Whereas the magnesium and perchlorate systems tend to possess higher surface temperatures and greater flame transfer distances. In addition, the sugar/chlorate/acid systems are spontaneously ignitable. In an effort to obtain a mixture which possessed many or all of these qualities, various combinations of these systems were tested. The results are shown in Table IX.

These results indicate that the presence of the third chemical tends to detract from the desirable results obtained with the two chemicals. For example, the addition of magnesium to the sugar/chlorate system increased the ignition time. However, it also increased the maximum surface temperature. The presence of the sugar in this mixture caused the maximum surface temperature and the maximum flame transfer distance to be lower than in a similar mixture without the sugar.

TABLE IX
EFFECTS OF MULTIPLE COMBINATIONS

Mixture	Ign Time (sec)	Ign Temp (°C)	Surf Temp (°C)
10% NaClO ₃ 7.5% Sugar	37	900	450
10% NaClO ₃ 7.5% Sugar 2.5% Mg	59	875	505
10% NaClO ₃ 7.5% Sugar 5% Mg	120		
15% NaClO ₃ 5% Sugar	24	640	460
15% NaClO ₃ 5% Sugar 5% Mg	32	665	545
15% NaClO ₃ 5% Mg	No Ignition	705	995
10% KClO ₃ 5% Mg	No Ignition	780	580
10% KClO ₃ 5% Mg 2% Sugar	25	525	535
10% KClO ₃ 5% Mg 2% Sugar 10% KClO ₄	45	820	

C. SIMULATION TESTS

The first series of tests, which were conducted to determine if a mixture containing 5% phosphorous and 10% potassium chlorate could be ignited inside a closed container, were partially successful. The

test mixture could be ignited inside the container provided two conditions were met: (1) a gasless initiator was used, and (2) some air space was present in the container.

A number of different types of initiators were used in these tests including pyrocore, Horex #1, and different size blasting caps. These initiators were unsatisfactory since they produced too much pressure and broke open the container. However, these initiators usually did ignite the fuel mixture, most of which was left in the container.

A combination of 1 part zirconium and 2 parts red iron oxide was used as the gasless initiator. This mixture was ignited using a standard black powder fuze. About 2 to 3 grams of this mixture were used since it did not break the container, yet it ignited the fuel inside. The fuel continued to burn until the oxygen in the container was consumed. The oxidizer, which had been added to the fuel, did not provide enough oxygen to support combustion. A similar test was performed on the plain gelled fuel with no additives. It was not ignited inside the closed container.

The second series of tests showed that the mixtures could not be ignited by a bursting type of charge. For these tests, small blasting caps surrounded by a booster charge of zirconium and red iron oxide were used as the bursting charges. These charges successfully shattered the container and spread the fuel mixture, however, none of the mixture was ignited. Other fuel mixtures with varying oxidizer concentrations were tested in the same manner. The mixture, with the minimum oxidizer concentration required for ignition, contained 5% red phosphorous and 25% potassium chlorate. The gel from these tests was so widely scattered, however, that the flames were soon extinguished by the wind.

During the third series of tests, a number of attempts to photograph the ignition sequence were made. Three of these attempts were successful. The first mixture which was photographed contained 10% sodium chlorate and 3% sugar. This mixture was burning in the container prior to impact. The film shows that when the container impacted, the mixture was dispersed but not all of it was ignited. The flames from the burning portion quickly spread to the unlit gel which was lying on the ground.

The results from the final two tests were identical. One of the test mixtures contained 15% sodium chlorate and 3% sugar. The other mixture contained 10% potassium chlorate and 3% sugar. In both of these tests the container impacted prior to the ignition of the gel inside. The films show that the mixtures ignited spontaneously within one or two seconds after impact. The flames then spread to the remaining gel.

These results also show that the effectiveness of this means of igniting the fuel is independent of the concentration or the type of chlorate used in the mixture. The minimum chlorate concentration required for ignition is probably about 8 or 9 percent. An analysis of these results indicates that this method of ignition is not superior to the present system of fuzing incendiary weapons since the flame spread did not occur at time of impact. However, the speed of flame spread may have been faster since the mixture had been heated by the chemical reaction prior to impact.

IV. DISCUSSION OF RESULTS

As shown in Table I, the combination of red phosphorous and a chlorate produced the lowest ignition temperature of any of the systems tested. The amount of this temperature reduction was directly proportional to the ease with which the reaction between the additives proceeded. The phosphorous/chlorate combination, when not mixed in the fuel gel, was extremely sensitive and could be made to react by simply stirring the two chemicals together. In contrast to this the phosphorous/perchlorate and the magnesium systems required a heat source to initiate the reaction. The ease with which these reactions were initiated is a measure of the activation energy for them. From this investigation, it is apparent that any reactants with a low activation energy would aid in sensitizing the basic fuel.

During the ignition temperature tests, a close observation of the gel surrounding the heating element was made. As the element was heated, the gel in contact with the wire began to melt. At about 100°C a noticeable amount of white vapor was emitted. At about 900°C the gel ignited. For mixtures which contained other chemical additives, the same sequence of events occurred. In addition, at some moderate temperature, which was a function of the chemicals added, small localized reactions took place which were identified by small flashes. As the temperature was increased, one of these localized reactions would produce enough heat to ignite the fuel. If none of the small reactions ignited the fuel, the heating element would ignite the fuel at about 900°C. For the mixtures shown in the

tables of results, the small local reactions started approximately 100° before the average ignition temperature. Due to the variations in concentrations, the ignition temperatures of most of the mixtures varied over a range of temperatures about 150 Celsius degrees.

The test results indicate that some of the mixtures had a flame transfer distance which was equal to or greater than the distance for gelled gasoline. The method of flame transfer was different in each case however. For the various fuel mixtures, the gel melts as it burns. As it liquifies, the solid additives settle to the surface under the burning mass. As the fuel is consumed, the solid additives near the edge of the burning material are ignited. Once ignited, most of the additives burned hotter and more violently than the basic fuel. The violence of this reaction caused the flames to shoot out, and in turn ignite the adjacent samples of the gel. In the magnesium systems white hot sparks were thrown out during the secondary reaction. It was observed that these sparks ignited samples of the gel at greater distances than the flames alone ignited them.

Since this method of flame transfer is the result of a secondary reaction, it is not available for flame spread on impact of the weapon. The flame transfer in a gasoline fueled weapon is accomplished by means of the volatile components which form a bridge for the flame transfer. This method of flame transfer is most effective on weapon impact, and its effectiveness diminishes with the length of time the gasoline gel is exposed to the air.

The method of flame transfer is closely allied to the speed of flame propagation. The flame spreads rapidly along a gasoline mixture because the volatile components form a combustible mixture with the

air. The flame spread along the hydrocarbon fuel is much slower since the flash point is above room temperature. Consequently the mixture must be heated to its flash point prior to ignition. The flame propagation process can be considered to be an infinite number of heating and ignition cycles which take place on an infinitesimal scale. The sum of the times required for each infinitesimal cycle is in effect the time required for the flame to propagate across a known distance. Therefore, the only mixture which could be expected to have a greater flame speed is the mixture containing sugar, a chlorate and sulfuric acid. This mixture is preheated by the chemical reaction and therefore its flame speed should be greater. An accurate measurement of the flame speed could not be obtained from the high speed films since the camera speed could not be accurately measured.

V. CONCLUSIONS

On the basis of the results obtained, it was concluded that the sensitivity of a basic jet fuel could be increased by the addition of solid chemicals. However, its ignitability cannot be improved sufficiently so that its performance is equivalent to gasoline. The sensitivity of the fuel was improved by three principal means.

(1) The addition of 5% magnesium and 10% potassium perchlorate significantly increases the flame transfer distance and therefore aids in flame propagation. This combination also increases the surface temperature, and therefore makes the fuel more effective as an incendiary weapon.

(2) The addition of 5% red phosphorous and 10% sodium chlorate or potassium chlorate increases the fuel's sensitivity to heat and thereby reduces the ignition difficulties.

(3) The chlorate/sugar/sulfuric acid additives can be used in lieu of or in conjunction with the standard ignitors in firebombs. Since these chemicals are sufficient to cause flames by themselves, they would aid ignition from an outside source when thoroughly mixed with the basic fuel.

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13. ABSTRACT Jet aircraft fuels are relatively stable and safe to handle. Therefore they are not readily adaptable to weapons applications. A study of the sensitization of the jet fuel with solid additives was carried out. Comparisons between the mixtures with the different solid additives were made to determine the best ones. An investigation of different ignition methods was also made to find a practical means of igniting the mixture. The results indicated that the jet fuel could be sensitized using a strong oxidizer in conjunction with either magnesium or red phosphorous. The fuel can also be ignited with a combination of chemicals which produce a spontaneous reaction.			

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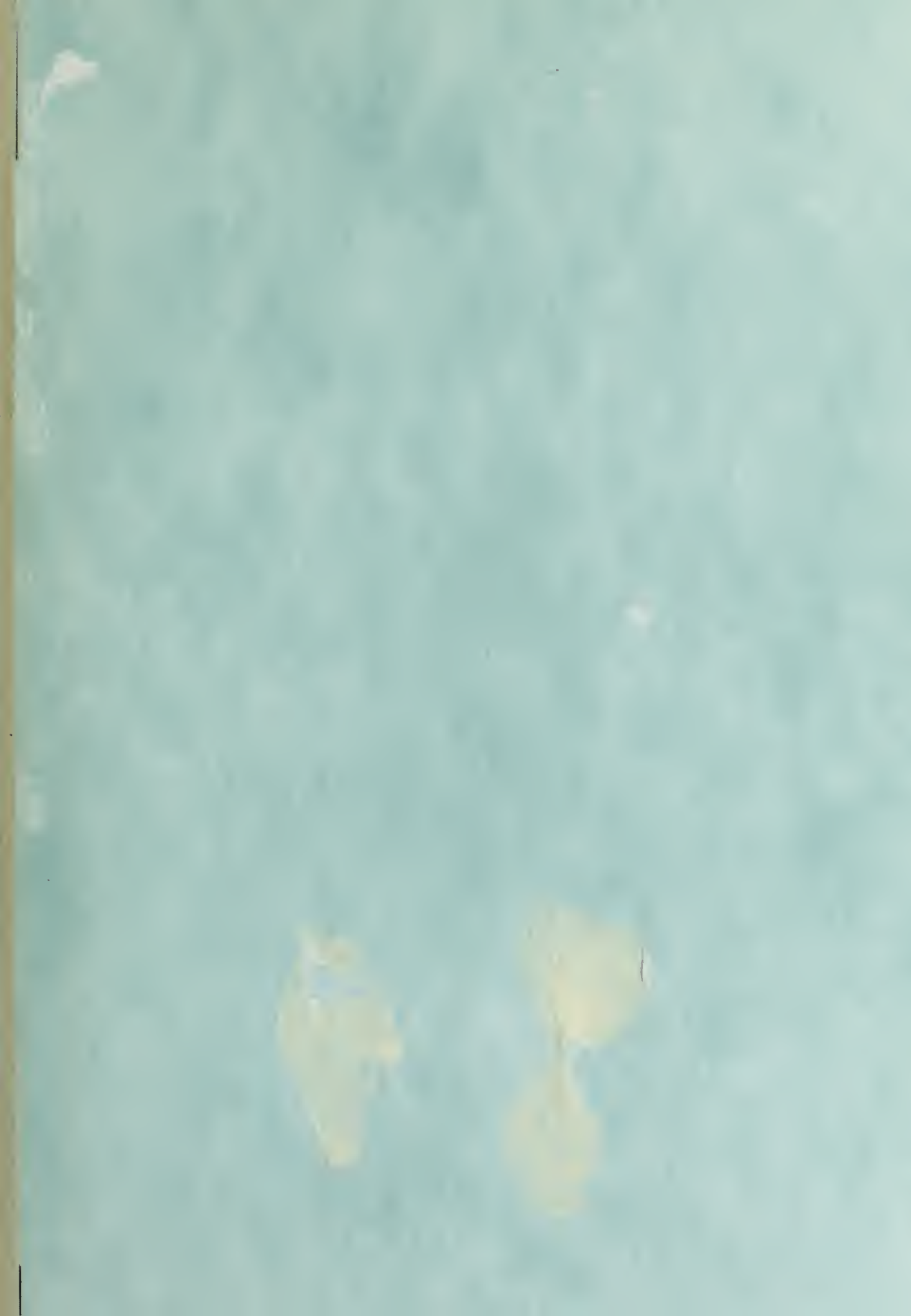
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